

Research Article

Influence of wheelchair user interface and personal characteristics on static and dynamic pretibial skin pressures in elite wheelchair racers, a pilot study

Ian Rice, Joseph Peters, Laura Rice, Yih-Kuen Jan 

Department of Kinesiology and Community Health, College of Applied Health Sciences, University of Illinois at Urbana-Champaign, Illinois, USA

Context/objective: To examine personal (athletic classification, age, sex, body mass index, duration of disability, tactile sensation of lower extremities) and wheelchair (kneeling plate angle) factors associated with increased pretibial skin pressures in elite wheelchair racers.

Design: Cross-sectional study.

Setting: University-based laboratory in Champaign, USA.

Participants: A convenience sample of elite wheelchair races with traumatic spinal cord injury and spinal disease were recruited for participation.

Interventions: Interface pressure mapping was used to examine athletes' average and peak pretibial skin pressures in their own racing wheelchairs during static and dynamic (propulsive) conditions on a dynamometer.

Outcome measures: The study examined associations between personal and wheelchair factors and pressure, differences in pressure between static and dynamic conditions, and the influence of athletic classification (T53 vs. T54) on kneeling plate angle preference and skin pressure magnitudes.

Results: Increased kneeling plate angle was moderately associated with dynamic pressures. T53 athletes utilized more vertical kneeling angles and experienced larger average and peak pressures during propulsion. Duration of disability was negatively associated with all measures of pressure. Overall, mean dynamic peak pressure was significantly greater than mean static peak pressure.

Conclusion: This pilot study represents a first step in understanding the influence of user interface on potentially injurious skin pressures in wheelchair racers. Vertical kneeling plate configurations were associated with increased pressures while increased years with disability was associated with lower pretibial pressures. In addition, T53 athletes with less trunk function may be at a greater risk for experiencing larger interface pressures than T54 athletes.

Keywords: Pressure ulcers, Sports for persons with disabilities, Spinal cord injuries

Introduction

Although adapted sport offers countless physiological and psychosocial benefits to participants, these activities do not occur without risk. For example many adapted sports, like wheelchair racing, may contribute to or exacerbate disability specific conditions like autonomic dysreflexia, thermal regulatory dysfunction, upper extremity integrity, and pressure ulcers (PU).

PU are a significant concern to wheelchair users in the general population and may represent a rising concern among adapted athletes.¹⁻³ PU can be defined as a soft tissue injury stemming from unrelieved pressure over a bony prominence that becomes ischemic and/or necrotic.⁴ Common extrinsic factors for PU development include pressure, shear, friction, immobility, moisture and wheelchair configuration, while intrinsic factors may include local infection, decreased autonomic control, age, anemia, malnutrition, sensory loss, spasticity, body mass index (BMI), sex and more.⁵⁻⁹

Correspondence to: Ian Rice, Department of Kinesiology and Community Health, College of Applied Health Sciences, University of Illinois at Urbana-Champaign, 2003 Huff Hall, M/C 586, 1206 S. Fourth St., Champaign, IL 61820, USA. Email: ianrice@illinois.edu
Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/yscm.

Unfortunately, PUs can be disruptive to both an individual's athletics career and everyday functioning and health. For example, pain and infection associated with PU can easily sideline athletes from sports participation for years.^{10,11} Although PU can be prevented through repositioning, proper hygiene, and other behavioral strategies,¹² unsuccessful management can disrupt physical, psychological and social wellbeing and may even lead to death.^{13,14}

Similar to the occurrence of PU in general populations of wheelchair users, athletes may be susceptible due to the interaction of numerous simultaneously occurring risk factors. More specifically, inherent disability characteristics^{15,16} combined with sport-specific wheelchair user interface factors and training routines may leave adapted athletes uniquely vulnerable to skin injuries. For example, athletes with SCI, who possess reduced sensation, paralysis, muscle atrophy, and compromised blood circulation often utilize rigid, tightfitting equipment designed for speed, not comfort. These factors, coupled with hours of intense training time and reduced opportunity for pressure reliefs, creates an ideal environment for skin breakdown. In fact, the time spent in a racing wheelchair (RWC) may exceed conditions the National Health Services cites as sufficient for the development of stage III or IV PU.¹³

Accordingly, reports of PU in wheelchair racers, although limited, may reflect these aforementioned concerns. For example, in a study surveying 291 adapted athletes, approximately 7% reported PU resulting from sport participation. More recently, 14% of wheelchair racers at the Junior National Wheelchair Games reported PU development,¹⁷ while Derman *et al.*¹⁸ reported skin injuries accounting for approximately 20% of ailments at the 2012 Paralympic Games. Ultimately, these trends may suggest the prevalence of PU in adaptive sports is on the rise.

Importantly, because much the aforementioned literature is dated, the location and magnitude of PU may not be entirely reflective of modern, adapted sports seating systems.¹⁹ For example, modern wheelchair racers have evolved from upright seating systems with foot plates to kneeling configurations, which rely on aluminum or carbon fiber kneeling plates positioned under the shin region of athletes. Importantly, the shin or pretibial region assumes the athlete's base of support rather than the buttocks region. Accordingly, the modern RWC's tendency to shift a majority of the racer's body weight over the pretibial region may represent a health concern. Moreover, skin injury to the pretibial area may be particularly difficult to heal because the skin in this region is thin, blood supply is low, and the risk

of infection is high.²⁰ Currently, there is an absence of literature or guidelines pertaining to body positioning safety in adapted sports like wheelchair racing.

The purpose of this study was to examine personal and wheelchair factors associate with pretibial skin pressures in wheelchair racers during static (stationary) and dynamic (propulsive) conditions. Personal factors included athlete classification (T53 and T54), age, sex, BMI, duration with disability, and tactile sensation of lower extremities; while kneeling plate angle was the sole wheelchair factor. A convenience sample of elite T54 and T53 athletes were recruited for analysis. We hypothesized a more vertical kneeling angle would be associated with increased pretibial pressures (Hypothesis 1). Similarly, we anticipated athletes with greater trunk impairment (T53) would experience higher pressures than T54's since they typically utilize more vertical kneeling positions²¹ (Hypothesis 2). We also predicted age, reduced sensation, duration with disability, and BMI, would be positively associated with increased pretibial pressures for all individuals (Hypothesis 3). Finally, based on analogous findings in the context of everyday wheelchair users,²² we hypothesized dynamic pressure magnitudes would exceed those obtained statically for all individuals (Hypothesis 4).

Methodology

Study design

This research study is a cross-sectional design. Wheelchair racers at the University of Illinois at Urbana-Champaign (UIUC) were recruited between January 2017 and December 2017 for participation. Study participants were recruited via posting of flyers and face-to-face interaction with research staff. All study procedures were approved by the Institutional Review Board (IRB) at UIUC and written informed consent was obtained from athletes prior to participation. The study required approximately 45 minutes of participants' time.

Participants

Interested athletes were invited to participate in the study if they met the following inclusion criteria: (1) 18–65 years of age, (2) utilize a modern RWC seating configuration¹⁹ and were (3) elite level athletes. Athletes were considered “elite” if they had competed in a Paralympic Games, or competed in >5 races in the past year. Individuals were excluded from participation if they had an active pressure ulcer (>stage 1)²³ or any other health condition preventing sport participation. All participants were treated in accordance with UIUC and IRB standards of human subjects' research.

Equipment

Pressure sensor

Pressure was measured in individuals' personal RWCs using an interface pressure mat (CONFORMat 5330, Tekscan, Boston, MA, USA). Individual sensors (1.47 cm × 1.47 cm) are dispersed evenly throughout the mat, which has an effective measure area of 47.1 cm × 47.1 cm. System calibration was performed according to the manufacturer's guidelines.²⁴ The pressure mat was placed between the pretibial region of the lower leg and the kneeling plate (Fig. 1).

Dynamometer

One free-spinning wheelchair racing dynamometer (Standard Roller, Revolution Sports, Quebec, Canada) was used for static and dynamic testing.

Racing wheelchairs

See Table 1 for RWC characteristics. Athletes were examined using their personal RWCs which have rigid kneeling plates.²⁵

Data reduction

Pressure

Primary pressure metrics obtained were peak pressure (PP) and average pressure (AP) occurring between the pretibial region of the lower leg and kneeling plate at 10 Hz. Peak pressure describes the maximum pressure value occurring on the pretibial region over a 20-second trial. Once PP was located, the adjacent cells containing similarly, high pressure scores were averaged over the 20-second trial with PP to obtain average pressure.^{26,27}

Personal factors

Demographic measures included sex, age, BMI, type of disability, American Spinal Injury Association Impairment Scale (AIS),²⁸ duration of disability, level of lower extremity tactile sensation, athletic classification, wheelchair athletic experience, and sport wheelchair manufacturer. AIS scale was self-reported and only determined for individuals living with spinal cord injury or spina bifida. Level of sensation was self-reported and included as an ordinal variable and characterized at three levels (1–3): (1) no sensation, (2) partial sensation and 3 (full sensation). Partial sensation was defined as an individual having reduced sense of touch in their lower extremities where the ability to perceive sensory stimuli was intact, without the ability to feel superficial pain and/or changes in temperature.^{28–30} Athlete classification was determined by the International Paralympic Committee classification system for wheelchair track,³¹ which specifies eligibility based on disability specific activity limitations per sport.

The primary difference between the T53 and T54 classification is trunk innervation, where T53 athletes possess full function of the arms, but no abdominal or lower spinal muscle activity and T54 athletes have full upper muscle power in the arms and partial to full muscle power of the trunk.³¹

Wheelchair factors

Kneeling plate angle was the sole wheelchair factor obtained. It was measured with an inclinometer and defined as the angle of inclination above ground level (0 degrees). To perform this measurement, the inclinometer was placed on the ground and set to absolute zero, and then placed on the kneeling plate to determine the kneeling plate angle. See Fig. 2.

Procedures

Participants received a demographic survey followed by static and dynamic pressure assessments performed in their personal RWCs secured to a dynamometer (Fig. 1).

Pressure evaluation

Pressure assessments were administered during static and dynamic conditions. During static conditions, individuals maintained a “ready” stance for 20 seconds which reflects a racer's starting position, prior to the initiation of propulsion, or coasting position³² (Fig. 1). The individual was asked to lean forward in their RWC, with their hands close to the hand rims. The dynamic condition was employed to examine the effects of propulsion-specific body movements on pretibial pressures. Individuals were asked to propel at approximately 14 mph for 20 seconds. Speed intensities typically range from 12 to 17 mph in elite wheelchair racers during training sessions, therefore a moderate intensity of 14 mph was selected by the researchers.³³ Speed was measured from the angular rotation of a free-spinning dynamometer and converted to linear speed which was displayed on an iPad (Apple Inc., Cupertino, CA, USA) in real time for each participant.

Statistical analysis

Quantitative analysis was performed using SPSS version 24.0 (SPSS Inc., Chicago, IL, USA). Descriptive statistics were calculated for all variables to characterize the sample. Normality for all continuous variables was examined with the Shapiro–Wilks test. Pearson's chi-square test was used to examine differences in categorical (sex and disability type) and ordinal (level of sensation) demographic characteristics. The influence of athletic classification (T53 vs. T54) on kneeling plate angle, static AP, static PP, dynamic AP and dynamic PP was compared with one-way ANOVA. Paired *t*-test

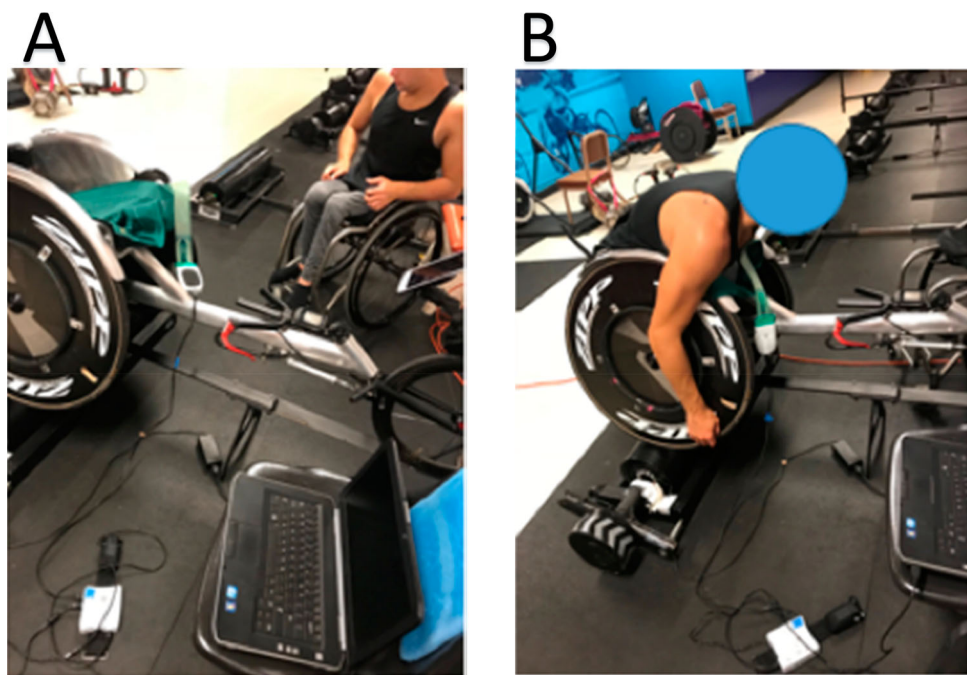


Figure 1 Pressure data collection.

was used to examine the overall group (T53 and T54) mean pressure difference between static and dynamic conditions. To examine the association between pressure and kneeling plate angle, age, sex, BMI and duration of disability, Pearson correlation analysis was used. To examine the relationship between pressure and sensation level, Spearman rank-order analysis was used because sensation level was a non-parametric ordinal variable.³⁴ A correlation coefficient of $\leq .30$ was considered weak, between $.30$ and $.60$ was considered moderate, and $\geq .60$ was considered strong.³⁵ Correlations were

reported for Pearson as r_p and Spearman as r_s . Statistical significance level was set *a priori* at $P < 0.05$.

Results

Demographics

See Table 1 for overall demographic characteristics. Nine (56%) males and seven (44%) females participated in this study. Their mean age was 25.50 ± 5.03 years and mean BMI was 20.82 ± 2.33 . Participants' diagnoses included spinal cord injury ($n = 11$, 69%), spina bifida ($n = 2$, 13%), transverse myelitis ($n = 2$, 13%) and

Table 1 Participant's demographic characteristics.

Sex	Age (y)	BMI (kg/m ²)	Disability	AIS	Years of Inj. (y)	RWC Class	Athlete Exp. (y)	RWC Year/Make
M	21	17.79	SCI – T8	A	9	T-53	4	'15 TE
F	20	20.56	SCI – T10	A	16	T-53	7	'08 TE
F	31	17.97	TM		26	T-53	20	'16 TE
M	23	21.53	SCI – T12	D	23	T-54	18	'16 TE
M	28	18.37	SCI – T10	B	28	T-53	28	'17 CB
M	22	24.03	SCI – T12	C	22	T-54	6	'12 TE
M	19	20.53	SB	C	19 (CG)	T-54	14	'15 EG
F	33	16.8	SCI – T11	C	28	T-54	15	'11 OE
F	23	18.88	SCI L1/L3	A	17	T-53	11	'16 TE
M	22	20.83	SB	D	22 (CG)	T-54	4	'16 EG
M	33	21.48	SCI – 6/T7	B	29	T-53	23	'14 TE
M	26	23.71	SCI – T10	A	4	T-53	2	'15 TE
M	34	23.67	SCI T7/T8	B	16	T-53	4	'14 TE
F	28	23.79	DM	NA	28 (CG)	T-54	10	'16 TE
F	21	21.03	TM	NA	20	T-53	10	'14 TE
F	24	22.13	SCI – T11	B	14	T-54	8	'16 TE

BMI, body mass index; AIS, American Spinal Injury Association Impairment Scale;²⁸ RWC Class = paralympic athletic classification; Years of Inj. = duration of disability; Athlete Exp., athletic experience; RWC, racing wheelchair; SCI, spinal cord injury; TM, transverse myelitis; SB, spina bifida; DM, diastematomyelia; CG, congenital; TE, top end; CB, carbonbike; EG, eagle; OE = OX engineering.

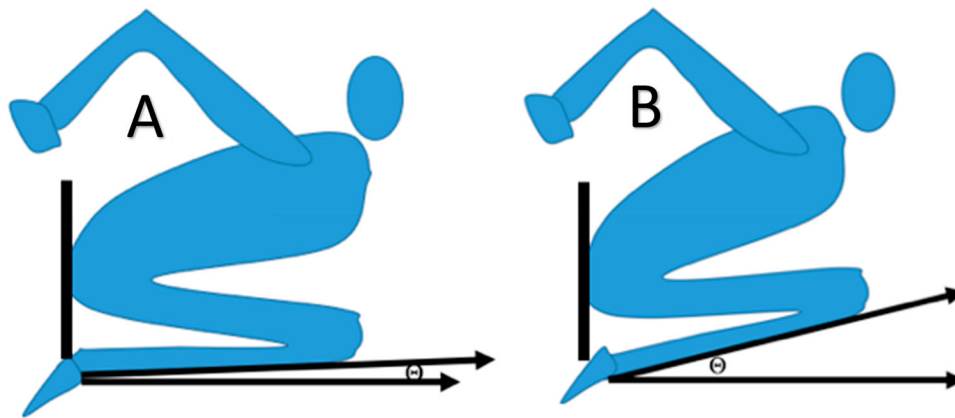


Figure 2 Kneeling plate angle.

diastematomyelia ($n = 1$, 6%). Nine (56%) were T-53 and seven (44%) were T-54. The mean years for duration of disability were $20.06 \text{ years} \pm 7.22$. The mean kneeling plate angle was 17.63 ± 13.07 . Mean demographic differences based on an athlete's classification can be found in Table 2. There were no significant demographic differences between groups with the exception of sensation level, where T54 athletes possessed greater tactile sensation than T53 athletes, $X^2 (2, N = 16) = 9.27$, $P < 0.05$.

Static vs. dynamic pressure conditions

Paired t -tests revealed dynamic PP was significantly larger than static PP (992.94 ± 311.18 vs. $907.69 \pm$

277.00); $t(15) = -2.47$, $P = 0.03$. However, statistically significant differences were not found between dynamic AP and static AP (819.85 ± 294.04 vs. 854.48 ± 273.70); $t(15) = 1.90$, $P = 0.08$. Finally, Pearson correlations (Table 3) revealed strong associations between static AP and dynamic AP ($r_p = .97$, $P = 0.00$), and static PP and dynamic PP ($r_p = .90$, $P = 0.00$).

Wheelchair and personal factors related to pressure

See Table 3. Duration with disability was significantly correlated with dynamic AP and PP ($r_p = -.52$, $P = .04$); ($r_p = -.60$, $P = .01$), respectively. However, age, sex, and BMI were not significantly correlated with dynamic pressure. Kneeling plate angle approached a significant correlation with dynamic AP ($r_p = .45$, $P = .08$), and was significantly correlated with dynamic PP ($r_p = .52$, $P = .04$). No significant correlations were observed between sensation and dynamic pressure. Duration with disability was significantly correlated with static AP and PP ($r_p = -.55$, $P = .03$); ($r_p = -.57$, $P = .02$), however age, sex and BMI were not significantly correlated with static pressure. Kneeling plate angle was not significantly correlated with static AP ($r_p = .35$, $P = .18$) or static PP ($r_p = .37$, $P = .16$). No significant correlations were observed between sensation and static pressure.

Pressure based on athletic classification

See Table 4. A significant difference in kneeling plate angle was found based on athlete classification [$F(1,14) = 7.03$, $P = 0.02$] where mean angle for T54 classification was significantly less than athletes in the T53 classification ($9.57^\circ \pm 12.49$ vs. $23.89^\circ \pm 9.16$). There was a significant effect of athletic class on dynamic AP [$F(1,14) = 4.79$, $P = 0.05$] where T54 athletes demonstrated reduced magnitude of AP than T53

Table 2 Demographic characteristics based on athletic classification.

Demographic characteristics	RWC classification	
	T-53 ($n = 9$)	T-54 ($n = 7$)
Age (y)	26.33 ± 5.43	24.43 ± 4.65
BMI (kg/m^2)	20.38 ± 2.30	21.38 ± 2.43
Height (m)	$1.63 \pm .12$	$1.57 \pm .15$
Weight (kg)	54.48 ± 12.77	53.01 ± 10.74
Years of Inj. (y)	18.33 ± 8.47	22.29 ± 4.92
Athlete Exp. (y)	10.33 ± 7.22	10.57 ± 5.03
Sex (M/F)	(5/4)	(4/3)
Sensation(N/P/F)*	(4/4/1)	(1/0/6)
Disability type (SCI/SB/TM/DM)	(7/0/2/0)	(4/2/0/1)

BMI, body mass index; Years of Inj. = duration of disability; Athlete Exp., athletic experience.

Sensation (N, None; P, Partial; F, Full)

SCI, spinal cord injury; SB, spina bifida; TM, transverse myelitis; DM, diastematomyelia.

Continuous variables reported as mean \pm SD, examined with ANOVA.

Categorical variables (sex and disability) reported as frequency, examined with Chi-square.

Sensation scale reported as (0–2) where 0 = none, 1 = partial, 2 = full, examined with Chi-square.

* $P < 0.05$.

^a < 1.0 .

Table 3 Correlational analysis for static and dynamic conditions.

Outcome measures	Static pressure variables				Dynamic pressure variables			
	AP (mmHg)		PP (mmHg)		AP (mmHg)		PP (mmHg)	
Age (y)	$r_p = -.16$	$P = .55$	$r_p = -.14$	$P = .59$	$r_p = -.16$	$P = .56$	$r_p = -.34^M$	$P = .20$
Sex (M/F)	$r_p = -.37$	$P = .16$	$r_p = -.42$	$P = .11$	$r_p = -.25$	$P = .36$	$r_p = -.25$	$P = .35$
BMI (kg/m ²)	$r_p = .24$	$P = .37$	$r_p = .24$	$P = .37$	$r_p = .14$	$P = .62$	$r_p = .17$	$P = .53$
Years of Inj. (y)	$r_p = -.55^{*,M}$	$P = .03$	$r_p = -.57^{*,M}$	$P = .02$	$r_p = -.52^{*,M}$	$P = .04$	$r_p = -.60^{*,S}$	$P = .01$
Athlete Exp. (y)	$r_p = -.38^M$	$P = .14$	$r_p = -.44^{a,M}$	$P = .09$	$r_p = -.37^M$	$P = .15$	$r_p = -.38^M$	$P = .14$
Kneel Angle (°)	$r_p = .35^M$	$P = .18$	$r_p = .37^M$	$P = .16$	$r_p = .45^{a,M}$	$P = .08$	$r_p = .52^{*,M}$	$P = .04$
Dynamic AP	$r_p = .97$	$P = .00$	$r_p = .95$	$P = .00$	$r_p = .97^{*,S}$	$P = .00$	$r_p = .92^{*,S}$	$P = .00$
Dynamic PP	$r_p = .92^{*,S}$	$P = .00$	$r_p = .90^{*,S}$	$P = .00$	$r_p = .95^{*,S}$	$P = .00$	$r_p = .90^{*,S}$	$P = .00$
Sensation	$r_s = -.25$	$P = .35$	$r_s = -.22$	$P = .42$	$r_s = -.36^M$	$P = .17$	$r_s = -.41^M$	$P = .11$

BMI, body mass index; Years of Inj = duration of disability; Athlete Exp., athletic experience; AP, average pressure; PP, peak pressure.

r_p = Pearson correlation.

r_s = Spearman correlation.

Sensation scale reported as (0–2) where 0 = none, 1 = partial, 2 = full.

* $P < .05$

^a $P < 1.0$

^MModerate correlation.

^SStrong correlation.

athletes (656.89 ± 295.62 vs. 946.59 ± 235.07). Similarly, a significant difference was observed for dynamic PP as a function of group classification where magnitude of dynamic PP was less for T54 athletes than T53 athletes (824.00 ± 337.24 vs. 1124.33 ± 227.76); $F(1,14) = 4.53$, $P = 0.05$. Finally, significant differences were not observed for static AP and PP as a function of group classification $F(1,14) = 4.12$, $P = 0.06$; [$F(1,14) = 3.41$, $P = 0.09$].

Discussion

The purpose of this pilot study was to examine personal and wheelchair factors, related to increased pretibial skin pressures in elite wheelchair racers. Given the paucity of literature regarding factors influential to skin pressures in adapted athletes, the current pilot study was exploratory in nature. The influence of wheelchair characteristics (H1), classification (H2), and other

personal factors (H3) on pressures were more pronounced during dynamic conditions, however, the same metrics obtained statically followed similar trends. Consistent with H1, increased kneeling plate angle was associated with increased dynamic AP and PP. Consistent with H2, T53 athletes were found to use a more vertical kneeling position than T54 athletes. Unexpectedly and counter to H3, duration of disability was negatively correlated with all measures of pressure both statically and dynamically, while other personal factors like age, lower limb sensation, and BMI were not significantly associated with pressures. Finally, consistent with H4 pressures recorded dynamically exceeded those obtained statically.

Although our study outcomes differed by condition (static vs. dynamic), the magnitude of these differences were less striking than those reported in the literature on every day wheelchair propulsions.^{36,37} For example, magnitude of mean PP was greater dynamically (992.94 mmHg vs. 907.69 mmHg) however, mean pressures obtained statically for both PP and AP were strongly correlated to the analogous metrics obtained dynamically. That is, according to our findings, athletes experiencing high pressures statically (e.g. in starting position or coasting) could expect to experience similar to higher pressures dynamically. Likewise, the strength of relationship demonstrating higher pressure with more vertical kneeling plate angles was stronger dynamically with pressures of greater magnitude, than the analogous metrics observed statically. Moreover, many of the findings which approached statistical significance ($P < 0.1$) statically may have reached statistical significance with a larger sample size.

Table 4 Athlete classifications' effect on pressures.

Outcome measures	RWC Class	
	T-53 (n = 9)	T-54 (n = 7)
Kneeling angle(°)*	23.89	9.57
Static AP (mmHg) ^a	965.94 ± 210.16	711.18 ± 292.90
Static PP (mmHg) ^a	1012.33 ± 224.41	773.14 ± 295.17
Dynamic AP (mmHg)*	946.59 ± 235.07	656.89 ± 295.62
Dynamic PP (mmHg)*	1124.33 ± 227.76	824.00 ± 337.24

RWC Class = paralympic athletic classification; AP, average pressure; PP, peak pressure.

Continuous variables reported as mean \pm SD, examined with ANOVA.

* $P < 0.05$.

^a $P < 1.0$.

The unique user interface and propulsion biomechanics inherent to wheelchair racing may offer clues regarding our results. For example, it is possible that upper limb and trunk motions during propulsion may have contributed to increased pretibial pressures during phases of the stroke where trunk interplay with thighs and/or hand-rim reaction forces, made a difference.³⁸ Also, increased kneeling angle (more vertical kneeling plate position), may allow individuals to more easily flex and extend the trunk off of the lap during a propulsion cycle which promotes both breathing and force transfer to the hand-rims with the hands.^{21,39} Conversely, when an athlete's lap is low (kneeling plate angle towards horizontal), the effects of gravity become more pronounced when athletes initiate trunk extension, particularly in the absence of full trunk innervation, which is more consistent with T53 athletes.

Since T53 athletes in the current study were found to use an elevated kneeling angle, they should be cautious of skin breakdown in the shin region as these athletes also demonstrated reduced sensation compared to T54 athletes. Implementing strategies to lower the kneeling plate angle, while stabilizing the trunk to prevent fatigue and performance degradation could be an option for athletes with less trunk function. For example, innovative racers have customized their frames to prop up the trunk with a chest block which permits the use of a kneeling plate angle towards horizontal. This technique also creates a pocket of space between the abdomen and lap, which may improve

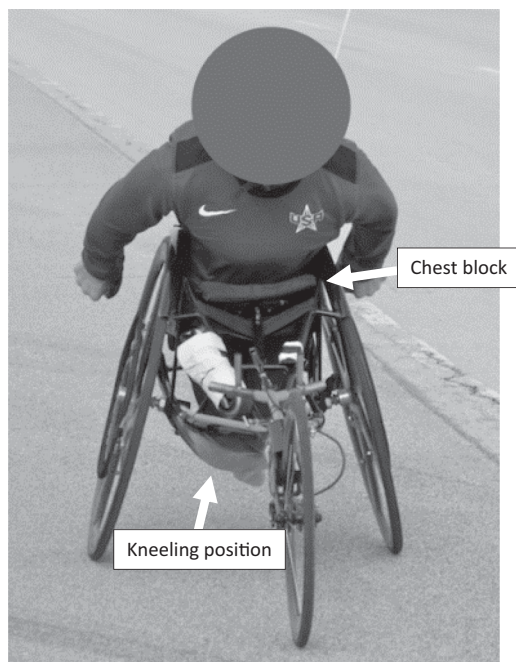


Figure 3 Innovative chest block design.

breathing as the abdomen is not compressed or restricted during propulsion (See Fig. 3).

Personal factors beyond athlete classification were also impactful to pretibial skin pressures in the current study. Counterintuitively, duration of disability was found to be negatively associated with both static and dynamic pressures. According to Chen *et al.*, as age and years increase following a spinal cord injury, so does one's risk for developing PU.⁴⁰ Although it would be premature to suggest experience counteracts the effects of age, our findings indicate that factors influenced by experience (knowledge, skill, training, etc.) may have contributed to the selection of more protective seating positions for pressure. Other personal factors like sex, BMI, age, and sensation were not correlated with pressures. Interestingly, the absence of a direct association between sensation and pressure in the current study competes against findings by Fuhrer *et al.*¹⁶ and Lewis *et al.*² who reported adapted athletes often place a low priority on comfort because of the inability to detect pain, thus increasing PU risk.² However, we did observe athletes with less functional ability (T53) utilize elevated kneeling angles and experienced higher pressures. Clearly more work is needed, with longer follow-up to more precisely characterize the individual and combine contributions of these personal and wheelchair characteristics for pressure and PU risk. It is plausible that our elite athletes possessed other protective characteristics or habits that other general population recreational adapted athletes do not. For example, participants in the current study were highly trained athletes with BMIs lower than reported in related studies ($20.9 \pm 2.8 \text{ kg/m}^2$ compared to $24.3\text{--}26.9 \text{ kg/m}^2$).^{41–44} However, the implications of low BMI are less clear since high BMI has been found to be both protective⁴⁵ and predictive⁴⁶ for PU risk.

As the current pilot study represents a first step in the examination of skin pressure in adapted athletes, a number of limitations must be acknowledged. For example, as a cross-sectional design, we cannot claim causal effects on pressures. Future studies should follow athletes longitudinally to verify the effects of personal and wheelchair factors on pressure and skin health. Next, the population utilized in this study were elite athletes which may not be reflective of novice or recreational athletes. Also, athlete's center of mass directed through the trunk was not accounted for which may have influenced location of pressure application to the pretibial region slightly. Development of segmental free body diagrams can be implemented to clarify. Also, the extent to which body repositioning occurred during dynamic conditions was not recorded. During dynamic capture of

pressure, body repositioning may occur where interface pressure distribution changes as bony structures like the ischial tuberosity shift and/or translate with propulsive motions.^{22,47} In essence, changes in the peak pressure locations may change during everyday propulsion where greater room for translation *in vivo* may create larger pressure gradients and shearing effects at the tissue-support interface, thus increasing PU risk.²² However, the modern racing frame may protect from translation because one's body is firmly wedged into a kneeling position, where the pretibial region is blocked both anteriorly by the kneeling plate and posteriorly by the rear frame and upholstery. For this reason, we did not anticipate the likelihood that translation of the bony prominence of the tibia would present the same risk as conditions under which the ischial tuberosity can translate during everyday propulsion. However, the lack of space and biological padding between the skin and bone at the pretibial region may put racers at a greater risk for developing tissue ischemia from compressive loading of the tissue.⁴⁸ Of note, junior and novice racers often utilize less customized, more spacious frames, which may allow pelvic repositioning similar to those observed in everyday wheelchair users, and should be accounted for in future investigation.⁴⁹

Pressure recorded during dynamic conditions in the current study was also limited to steady state speeds during dynamometer propulsion. Other common racing scenarios like turning, accelerations, or even rough over ground surfaces may alter or amplify pressures.^{37,50} Also, the testing speed of 14 mph is not reflective of the entire range of speeds that racers experience. Most importantly, the assessment of pressure in isolation is not sufficient to definitively predict PU risk.²⁶ Factors such as tissue hydration, metabolism, and nutrition were not examined and can influence risk. In addition, comparing our results to related studies may be complicated by methodological variations. For example, studies often define and quantify pressures differently, where pressure sensing mats may differ by number of sensor cells, calibration, and maximum pressure sensing capabilities.^{2,3,27,22,51,26,52}

Disclaimer statements

Contributors None.

Funding The Paralyzed Veterans of America Education Foundation, Grant # 817 supported this work.

Conflicts of interest None.

Ethics approval None.

ORCID

Yih-Kuen Jan  <http://orcid.org/0000-0001-7149-4034>

References

- Mutsuzaki H, Tachibana K, Shimizu Y, Hotta K, Fukaya T, Karasawa M, *et al.* Factors associated with deep tissue injury in male wheelchair basketball players of a Japanese national team. *Asia-Pacific J Sports Med Arthroscopy Rehab Technol* 2014;1(2):72–6.
- Lewis A, Phillips E, Grimshaw P, Portus M, Robertson WSP. Effect of seating cushions on pressure distribution in wheelchair racing. *ISBS Proc Arch* 2017;35(2007):875–8.
- Berthold J, Dicianno BE, Cooper RA. Pressure mapping to assess seated pressure distributions and the potential risk for skin ulceration in a population of sledge hockey players and control subjects. *Disability Rehab Assist Technol* 2013;8(5):387–91.
- Janis JE KJ. Pressure sores. *Sel Read Plast Surg* 2003;9(39):1–42.
- Kruger EA, Pires M, Ngann Y, Sterling M, Rubayi S. Comprehensive management of pressure ulcers in spinal cord injury: Current concepts and future trends. *J Spinal Cord Med* 2013;36(6):572–85.
- Arthurs ZM, Cuadrado D, Sohn V, Wolcott K, Lesperance K, Carter P, *et al.* Post-bariatric panniculectomy: pre-panniculectomy body mass index impacts the complication profile. *Am J Surg* 2007;193(5):567–70; discussion 570.
- Lowe JR. Skin integrity in critically ill obese patients. *Crit Care Nurs Clin North Am*. 2009;21(3):311.
- Howard DL, Taylor YJ. Racial and gender differences in pressure ulcer development among nursing home residents in the Southeastern United States. *J Women Aging*. 2009;21(4):266–78.
- Saunders LL, Krause JS, Peters BA, Reed KS. The relationship of pressure ulcers, race, and socioeconomic conditions after spinal cord injury. *J Spinal Cord Med*. 2010;33(4):387–95.
- Jiricka MK, Ryan P, Carvalho MA, Bukvich J. Pressure ulcer risk factors in an ICU population. *Am J Crit Care* 1995;4(5):361–7.
- Gurtner GC, Werner S, Barrandon Y, Longaker MT. Wound repair and regeneration. *Nature* 2008;453(7193):314–21.
- Witkowski JA, Parish LC, Campbell C, Parish JL. Decubitus ulcers. In: Lebowitz MG, Heymann WR, Berth-Jones J, Coulson I, (eds.) *Treatment of Skin Disease: Comprehensive Therapeutic Strategies*. 4th ed. Philadelphia, PA: Elsevier Saunders; 2014: chap 52.
- Gefen A. How much time does it take to get a pressure ulcer? Integrated evidence from human, animal, and in vitro studies. *Ostomy Wound Manage*. 2008;54(10):26–28, 30–25.
- Lala D, Dumont FS, Leblond J, Houghton PE, Noreau L. Impact of pressure ulcers on individuals living with a spinal cord injury. *Arch Phys Med Rehabil* 2014;95(12):2312–9.
- Crane D HB. Pressure ulcers can wreck your life! Preventing and managing skin problems after SCI. 2012; www.sci.washington.edu.
- Fuhrer MJ, Garber SL, Rintala DH, Clearman R, Hart KA. Pressure ulcers in community-resident persons with spinal cord injury: prevalence and risk factors. *Arch Phys Med Rehabil*. 1993;74(11):1172–7.
- Wilson PE, Washington RL. Pediatric wheelchair athletics: sports injuries and prevention. *Paraplegia*. 1993;31:330.
- Derman W, Schwellnus M, Jordaan E, Blauwet CA, Emery C, Pit-Grosheide P, *et al.* Illness and injury in athletes during the competition period at the London 2012 Paralympic Games: development and implementation of a web-based surveillance system (WEB-IISS) for team medical staff. *Br J Sports Med* 2013;47(7):420–5.
- Cooper RA, De Luigi AJ. Adaptive sports technology and biomechanics: wheelchairs. *PM&R* 2014;6(8, Supplement):S31–S9.
- Bradley L. The conservative management of pre-tibial lacerations. *Nurs Times* 2002;98(8):62.
- Cooper RA, Cooper R, Susmarski A. Wheelchair sports technology and biomechanics. In: Di Luigi AJ, (ed.) *Adaptive Sports Medicine: A Clinical Guide*, 1st ed. Springer International Publishing; 2018. p. 21–34.

- 22 Tam EW, Mak AF, Lam WN, Evans JH, Chow YY. Pelvic movement and interface pressure distribution during manual wheelchair propulsion. *Arch Phys Med Rehabil* 2003;84(10):1466–72.
- 23 Bhattacharya S, Mishra RK. Pressure ulcers: current understanding and newer modalities of treatment. *Ind J Plast Surg* 2015;48(1):4–16.
- 24 Tekscan Incorporation. (2010). CONFORMat Seating/positioning Pressure Mapping System Version 7.2: User Manual. Boston, MA. 126–152.
- 25 Vanlandewijck Y, Theisen D, Daly D. Wheelchair propulsion biomechanics: implications for wheelchair sports. *Sports Med*. 2001; 31(5):339–367.
- 26 Sprigle S, Dunlop W, Press L. Reliability of bench tests of interface pressure. *Assist Technol* 2003;15(1):49–57.
- 27 Maurer CL, Sprigle S. Effect of seat inclination on seated pressures of individuals with spinal cord injury. *Phys Ther* 2004;84(3):255–61.
- 28 Kirshblum SC, Burns SP, Biering-Sorensen F, Donovan W, Graves DE, Jha A, *et al.* International standards for neurological classification of spinal cord injury (Revised 2011). *J Spinal Cord Med* 2011;34(6):535–46.
- 29 International Standards for Neurological Classification of Spinal Cord Injury (ISNCSCI). (2017, June 7). Physiopedia. Retrieved 14:35, July 19, 2018 from [https://www.physio-pedia.com/index.php?title=International_Standards_for_Neurological_Classification_of_Spinal_Cord_Injury_\(ISNCSCI\)&oldid=174770](https://www.physio-pedia.com/index.php?title=International_Standards_for_Neurological_Classification_of_Spinal_Cord_Injury_(ISNCSCI)&oldid=174770).
- 30 Siddall P, McClelland J. Non-painful sensory phenomena after spinal cord injury. *J Neurol Neurosurg Psychiatry* 1999;66(5): 617–22.
- 31 Explanatory guide to Paralympic classification in Paralympic summer sports, pages 9–10. Official website of the Paralympic Movement, International Paralympic Committee (IPC), [document on the Internet]. 2015, [updated 2015 September; cited 2018 July]. Available from https://www.paralympic.org/sites/default/files/document/150915170806821_2015_09_15%2BExplanatory%2Bguide%2BClassification_summer%2BFINAL%2B_5.pdf
- 32 Barbosa TM, Forte P, Estrela JE, Coelho E. Analysis of the aerodynamics by experimental testing of an elite wheelchair sprinter. *Procedia Eng* 2016;147:2–6.
- 33 Rice I, Dysterheft J, Bleakney AW, Cooper RA. The Influence of Glove type on simulated wheelchair racing propulsion: a pilot study. *Int J Sports Med* 2016;37(1):30–5.
- 34 Mukaka MM. A guide to appropriate use of Correlation coefficient in medical research. *Malawi Med J* 2012;24(3):69–71.
- 35 de Groot S, van der Woude LHV, Niezen A, Smit CAJ, Post MWM. Evaluation of the physical activity scale for individuals with physical disabilities in people with spinal cord injury. *Spinal Cord* 2009;48:542.
- 36 Kernozek TW, Lewin JE. Seat interface pressures of individuals with paraplegia: influence of dynamic wheelchair locomotion compared with static seated measurements. *Arch Phys Med Rehabil* 1998;79(3):313–6.
- 37 Dabnichki P, Taktak D. Pressure variation under the ischial tuberosity during a push cycle. *Med Eng Phys* 1998;20(4):242–56.
- 38 Goosey-Tolfrey VL, Fowler NE, Campbell IG, Iwnicki SD. A kinetic analysis of trained wheelchair racers during two speeds of propulsion. *Med Eng Phys* 2001;23(4):259–66.
- 39 Amazeen PG, Amazeen EL, Beek PJ. Coupling of breathing and movement during manual wheelchair propulsion. *J Exp Psychol Hum Percept Perform* 2001;27(5):1243–59.
- 40 Chen Y, Devivo MJ, Jackson AB. Pressure ulcer prevalence in people with spinal cord injury: age-period-duration effects. *Arch Phys Med Rehabil* 2005;86(6):1208–13.
- 41 Eriks-Hoogland I, Hilfiker R, Baumberger M, Balk S, Stucki G, Perret C. Clinical assessment of obesity in persons with spinal cord injury: validity of waist circumference, body mass index, and anthropometric index. *J Spinal Cord Med* 2011;34(4): 416–22.
- 42 Spungen AM, Adkins RH, Stewart CA, Wang J, Pierson RN, Waters RL, *et al.* Factors influencing body composition in persons with spinal cord injury: a cross-sectional study. *J Appl Psychol* 2003;95(6):2398–407.
- 43 Buchholz AC, McGillivray CF, Pencharz PB. Differences in resting metabolic rate between paraplegic and able-bodied subjects are explained by differences in body composition. *Am J Clin Nutr* 2003;77(2):371–8.
- 44 Desport JC, Preux PM, Guinvarc’h S, Rousset P, Salle JY, Daviet JC, *et al.* Total body water and percentage fat mass measurements using bioelectrical impedance analysis and anthropometry in spinal cord-injured patients. *Clin Nutr* 2000;19(3):185–90.
- 45 Compher C, Kinosian BP, Ratcliffe SJ, Baumgarten M. Obesity reduces the risk of pressure ulcers in elderly hospitalized patients. *J Gerontol – Ser A Biol Sci Med Sci* 2007;62(11):1310–2.
- 46 Baugh N, Zuelzer H, Meador J, Blankenship J. Wounds in surgical patients who are obese: Surgery, whether bariatric or not, puts this population at risk. Review the basics of prevention and care. *Am J Nurs* 2007;107(6):40–50.
- 47 Hobson DA, Tooms RE. Seated lumbar/pelvic alignment. A comparison between spinal cord-injured and noninjured groups. *Spine* 1992;17(3):293–8.
- 48 Eckrich KM, Patterson PE. Dynamic interface pressure between seated users and their wheelchairs. *Int J Indust Ergonom*. 1991;8(1):115–123.
- 49 Cooper, RA, Boninger, ML, Rice, I, Shimada SD, Cooper, RM. Elite athletes with impairments. 2nd ed. Champaign, IL: Human Kinetics Publishing; 2006.
- 50 Dabnichki PA, Crocombe AD, Hughes SC. Deformation and stress analysis of supported buttock contact. *Proc Inst Mech Eng Part H: J Eng Med* 1994;208(1):9–17.
- 51 Eckrich KM, Patterson PE. Dynamic interface pressure between seated users and their wheelchairs. *Int J Indust Ergonom* 1991;8(1): 115–23.
- 52 Lung C-W, Yang TD, Crane BA, Elliott J, Dicianno BE, Jan Y-K. Investigation of peak pressure index parameters for people with spinal cord injury using wheelchair tilt-in-space and recline: methodology and preliminary report. *BioMed Res Int*. 2014;2014:9.